

## FAR-INFRARED OBSERVATIONS OF RADIO QUASARS AND FR II RADIO GALAXIES

Y. SHI,<sup>1</sup> G. H. RIEKE,<sup>1</sup> D. C. HINES,<sup>1,2</sup> G. NEUGEBAUER,<sup>1</sup> M. BLAYLOCK,<sup>1</sup> J. RIGBY,<sup>1</sup> E. EGAMI,<sup>1</sup>  
K. D. GORDON,<sup>1</sup> AND A. ALONSO-HERRERO<sup>1,3</sup>  
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### ABSTRACT

We report MIPS photometry of 20 radio-loud quasars and galaxies at 24 and 70  $\mu\text{m}$  (and of five at 160  $\mu\text{m}$ ). We combine this sample with additional sources detected in the far-infrared by *IRAS* and *ISO* for a total of 47 objects, including 23 steep-spectrum type I AGNs: radio-loud quasars and broad-line radio galaxies; and 24 type II AGNs: narrow-line and weak-line FR II radio galaxies. Of this sample, the far-infrared emission of all but 3C 380 appears to be dominated by emission by dust heated by the AGN and by star formation. The AGN appears to contribute more than 50% of the far-infrared luminosity in most of the sources. It is also expected that the material around the nucleus is optically thin in the far-infrared. Thus, the measurements at these wavelengths can be used to test the orientation-dependent unification model. As predicted by the model, the behavior of the sources is consistent with the presence of an obscuring circumnuclear torus; in fact, we find that it may still have significant optical depth at 24  $\mu\text{m}$ . In addition, as expected for the radio-loud quasars, there is a significant correlation between the low-frequency radio (178 MHz) and the 70  $\mu\text{m}$  emission, two presumably isotropic indicators of nuclear activity. This result is consistent with the simple unified scheme. However, there is a population of radio galaxies that are underluminous at 70  $\mu\text{m}$  compared with the radio-loud quasars and hence are a challenge to the simple unified model.

*Subject headings:* galaxies: active — infrared: galaxies — quasars: general

### 1. INTRODUCTION

Unification models of active galactic nuclei (AGNs) hypothesize that apparently distinct types of AGN harbor intrinsically similar nuclear engines that may be described by a small number of fundamental physical parameters. For example, it is proposed that orientation-dependent obscuration by a torus surrounding the central supermassive black hole, along with beamed emission, is responsible for the large diversity in the appearance of radio-loud AGNs (as reviewed by, e.g., Urry & Padovani 1995). In the purest form of the model, the torus is always of the same geometry, so differences among sources arise only as a result of different inclinations relative to the observer and different AGN luminosities. In this paper, we focus on the unification initially proposed by Orr & Browne (1982) and Barthel (1989) for steep-spectrum radio quasars and FR II radio galaxies (Fanaroff & Riley 1974).

Recent *Infrared Space Observatory* (*ISO*) observations have shown that thermal emission by dust is the dominant infrared (IR) emission component for most steep-spectrum extragalactic radio sources (Haas et al. 1998; Polletta et al. 2000; van Bemmél & Barthel 2001; Andreani et al. 2002; Siebenmorgen et al. 2004). However, the relative luminosity contribution from star formation and from the nuclear engine is not clear. Polletta et al. (2000) suggest that the stellar-powered contribution to the IR emission is less than 27% on the basis of the relatively warm IR colors indicated by the ratio  $F(60\text{--}200\ \mu\text{m})/F(3\text{--}60\ \mu\text{m})$ . Although the IR emission from AGNs is generally warmer than that from star-forming regions, the IR color of AGNs can be affected by extinction, especially for misaligned sources, and the IR colors  $F(60\ \mu\text{m})/F(25\ \mu\text{m})$  of AGNs and star-forming regions have a large range (Kewley et al. 2001). Therefore, the color-based

arguments may not be rigorous. Theoretically, early models for AGNs (Pier & Krolik 1993; Granato & Danese 1994) underestimated the far-IR (FIR) emission from heated dust, which led Rowan-Robinson (2000) to suggest a star formation origin for most of the FIR emission, consistent with results of recent radiative transfer models (van Bemmél & Dullemond 2003). Recently, Nenkova et al. (2002) and Siebenmorgen et al. (2004) suggested that the nuclear engine can heat the dust to large distances from the galaxy center and therefore that star formation need play only a small role in the dust heating.

In this paper, we combine IR measurements of radio-loud AGNs obtained with the Multiband Imaging Photometer for *Spitzer* (MIPS; Rieke et al. 2004) and previous data from the *Infrared Astronomical Satellite* (*IRAS*) and *ISO*. We use these observations to show that the IR emission is usually dominated by radiation from dust heated by the AGN. Thus, we can use the far-infrared properties of these sources to gain new insights to unification models.

### 2. OBSERVATIONS

#### 2.1. *The Sample and Extended Sample*

We have used MIPS to observe 20 FR II radio galaxies and steep-spectrum radio quasars listed in Tables 1 and 2. The sample is drawn from Neugebauer et al. (1986) and Golombek et al. (1988), with priority on objects at  $z < 0.4$  and with good *Hubble Space Telescope* (*HST*) images. To complement these measurements, we defined an extended sample, consisting of the 27 additional 3CR sources listed in Table 3, all of which are detected by *IRAS* or *ISO* at a minimum of wavelengths between 10 and 200  $\mu\text{m}$ . The *IRAS* data are from the NASA/IPAC Extragalactic Database (NED), and the *ISO* data are from Haas et al. (2004), van Bemmél & Barthel (2001), and NED. The uncertainties in the *ISO* data from Haas et al. (2004) are quoted as 10%–30%; in this paper we adopt 30% uniformly. Except for Pic A and 3C 218, the sources belong to the parent 3CR sample.

<sup>1</sup> Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721.

<sup>2</sup> Currently at Space Science Institute, 4750 Walnut Street, Suite 205, Boulder, CO 80301.

<sup>3</sup> Now at Instituto de Estructura de la Materia, CSIC, Madrid, Spain.

TABLE 1  
MIPS MEASUREMENTS OF STEEP-SPECTRUM RADIO SOURCES

Source (1)	Integration Time (s) (2)	24 $\mu\text{m}$ (mJy) (3)	Integration Time (s) (4)	70 $\mu\text{m}$ (mJy) (5)
3C 48 .....	48.2	131.0 $\pm$ 0.09	37.7	696 $\pm$ 8
3C 61.1 .....	48.2	5.0 $\pm$ 0.07	125.8	30 $\pm$ 4
Pic A .....	165.7	130 $\pm$ 0.04	125.8	171 $\pm$ 5
3C 171 .....	165.7	7.5 $\pm$ 0.05	125.8	19 $\pm$ 3
3C 173.1 .....	165.7	0.51 $\pm$ 0.06	125.8	1.7 $\pm$ 2
3C 218 .....	165.7	8.6 $\pm$ 0.06	125.8	118 $\pm$ 5
3C 219 .....	165.7	12.7 $\pm$ 0.07	125.8	29 $\pm$ 5
3C 236 .....	165.7	17.4 $\pm$ 0.07	125.8	50 $\pm$ 3
3C 249.1 .....	48.2	45.0 $\pm$ 0.07	125.8	57 $\pm$ 2
3C 277.1 .....	48.2	19.8 $\pm$ 0.07	125.8	20 $\pm$ 2
3C 284 .....	165.7	24.6 $\pm$ 0.07	125.8	80 $\pm$ 2
3C 303.1 .....	165.7	7.6 $\pm$ 0.05	125.8	27 $\pm$ 15
3C 315 .....	165.7	1.9 $\pm$ 0.05	125.8	28 $\pm$ 4
3C 323.1 .....	48.2	33.0 $\pm$ 0.08	125.8	30 $\pm$ 2
3C 327 .....	165.7	245 $\pm$ 0.07	125.8	468 $\pm$ 7
3C 348 .....	165.7	0.25 $\pm$ 0.07	125.8	28 $\pm$ 5
3C 349 .....	165.7	$\leq$ 0.15	125.8	7 $\pm$ 3
3C 351 .....	48.2	103 $\pm$ 0.07	125.8	182 $\pm$ 3
3C 381 .....	165.7	46 $\pm$ 0.05	125.8	40 $\pm$ 3
3C 388 .....	165.7	2.34 $\pm$ 0.05	125.8	16 $\pm$ 3

NOTES.—Nominal photon noise errors are given to show the intrinsic signal-to-noise ratio for the measurements. Systematic calibration uncertainties are discussed in the text. The upper limit is at 3  $\sigma$  significance. The integration time at 160  $\mu\text{m}$  was 84 s per source. Sources detected at this wavelength are 3C 48, 1147  $\pm$  93 mJy; Pic A, 475  $\pm$  40 mJy; 3C 218, 211  $\pm$  31 mJy; 3C 327, 425  $\pm$  38 mJy; 3C 351, 182  $\pm$  21 mJy.

TABLE 2  
OTHER PROPERTIES OF THE MIPS SAMPLE

Source (1)	$M_B$ (2)	Type (3)	$z$ (4)	$F_{5t}$ (mJy) (5)	$F_{5c}$ (mJy) (6)	Reference (7)	Size (kpc) (8)	$\Gamma_X$ (9)	X-Ray ( $10^{-12}$ ergs $\text{s}^{-1}$ $\text{cm}^{-2}$ ) (10)	Line Ratio (11)	Reference (12)
3C 48 .....	-26.5	Q	0.367	5330 $\pm$ 70	896	1	2.4	2.12	2.39	-0.013	2
3C 61.1 .....	-21.3	NLRG	0.186	1900 $\pm$ 90	2.64	3	535	...	.....	0.47	4
Pic A .....	-19.5	BLRG	0.035	15500 $\pm$ 470	1004	3	281	1.69	8.66	0.62	5
3C 171 .....	-22.0	NLRG	0.238	1210 $\pm$ 60	1.68	3	31	...	...	0.79	6
3C 173.1 .....	-22.4	WLRG	0.292	770 $\pm$ 120	7.21	3	244	...	...	...	...
3C 218 .....	-22.4	NLRG	0.054	13100	245	3	...	1.79	0.224	-0.125	7
3C 219 .....	-22.5	BLRG	0.174	2270 $\pm$ 110	49.2	3	441	1.58	1.62	0.32	4
3C 236 .....	-21.6	WLRG	0.098	1330 $\pm$ 130	141	3	3956	...	...	0.57	4
3C 249.1 .....	-26.8	Q	0.311	780 $\pm$ 40	76	8	89	1.77	1.49	0.97	9
3C 277.1 .....	-24.7	Q	0.320	1040 $\pm$ 50	...	...	6.5	1.63	0.691	0.20	2
3C 284 .....	-21.5	NLRG	0.239	685 $\pm$ 60	3.2	10	635	...	...	...	...
3C 303.1 .....	-22.0	NLRG	0.267	457 $\pm$ 50	<4.7	3	9.6	...	...	...	...
3C 315 .....	-21.4	NLRG	0.108	1260 $\pm$ 60	<150	10	257	...	...	...	...
3C 323.1 .....	-24.3	Q	0.264	880	32	8	267	...	...	0.71	9
3C 327 .....	-21.9	NLRG	0.103	2740 $\pm$ 140	30.4	3	369	...	...	1.22	11
3C 348 .....	-22.2	NLRG	0.154	11800 $\pm$ 590	10.2	3	286	...	...	...	...
3C 349 .....	-21.1	NLRG	0.205	1130 $\pm$ 60	25.0	3	257	...	...	...	...
3C 351 .....	-27.7	Q	0.371	1200 $\pm$ 60	8.0	8	277	1.69	1.36	-0.016	12
3C 381 .....	-22.0	BLRG	0.160	1280 $\pm$ 50	5.12	3	177	...	...	1.26	13
3C 388 .....	-23.1	WLRG	0.090	1760 $\pm$ 40	59.0	3	48	...	...	0.49	4

NOTES.—Col. (3): emission-line type. NLRG: narrow-line radio galaxy; BLRG: broad-line radio galaxy; WLRG: weak-line radio galaxy; Q: quasar. Col. (5): 5 GHz flux density. Col. (6): Radio core flux at 5 GHz. Col. (7): References for col. (6). Col. (8): Linear radio size. The references for radio sizes are Akujor & Garrington (1995), Allington-Smith (1984), Gavazzi & Perola (1978), and Nilsson et al. (1993). Col. (9): Spectral index of hard X-ray emission over 2–10 keV in the rest frame, assuming a power-law SED. Col. (10): Rest-frame 2–10 keV absorption-corrected X-ray flux in the central 2.5' region. Col. (11): Logarithm of the ratio of the intensity of [O III]  $\lambda$ 5007 to H $\beta$ . Col. (12): References for col. (11).

REFERENCES.—(1) Akujor et al. 1991; (2) Gelderman & Whittle 1994; (3) Zirbel & Baum 1995; (4) Lawrence et al. 1996; (5) Tadhunter et al. 1993; (6) Solórzano-Iñarrea & Tadhunter 2003; (7) Simpson et al. 1996; (8) Kellermann et al. 1989; (9) Boroson & Oke 1984; (10) Giovannini et al. 1988; (11) de Grijs et al. 1992; (12) Corbin & Boroson 1996; (13) Grandi & Osterbrock 1978.

TABLE 3  
THE EXTENDED SAMPLE OF RADIO GALAXIES AND QUASARS

Source (1)	$M_B$ (2)	Type (3)	$z$ (4)	$F_{5t}$ (mJy) (5)	$F_{5c}$ (mJy) (6)	Reference (7)	$F_{24}$ (mJy) (8)	$F_{70}$ (mJy) (9)	$F_{160}$ (mJy) (10)	Size (kpc) (11)	$\Gamma_X$ (12)	X-Ray ( $10^{-12}$ ergs s $^{-1}$ cm $^{-2}$ ) (13)	Line Ratio (14)	Reference (15)
3C 2	-27.8	Q	1.037	1400 ± 70	50	1	...	91 ± 30	...	37	...	...	...	
3C 20	-21.9	NLRG	0.174	4150 ± 210	2.6	2	...	107 ± 35	162 ± 140	146	...	...	...	
3C 33.1	-22.2	BLRG	0.181	860 ± 40	14.02	3	42 ± 18	45 ± 15	...	614	...	...	...	
3C 47	-25.6	Q	0.425	1090 ± 50	77.9	4	42 ± 30	117 ± 37	165 ± 71	353	1.28	1.55	-0.18	5
3C 65	-24.9	NLRG	1.176	770 ± 120	0.50	3	24 ± 193 <sup>a</sup>	110 ± 20	42 ± 34	134	...	...	...	
3C 79	-23.9	NLRG	0.255	1300 ± 70	10.00	3	59 ± 15	141 ± 26	...	322	...	...	0.40	6
3C 109	-25.7	Q	0.305	1630 ± 160	305.85	3	165 ± 41	208 ± 34	...	403	1.69	8.66	...	
3C 111	-23.8	Q	0.049	7870 ± 393	...		213 ± 54	342 ± 100	...	244	...	...	...	
3C 234	-22.3	NLRG	0.184	1530 ± 50	95.79	3	259 ± 75	269 ± 54	...	317	...	...	0.48	6
3C 277.2	-23.9	NLRG	0.766	480	<15.04	3	...	122 ± 42	...	379	...	...	...	
3C 293	-21.5	WLRG	0.045	1857 ± 40	100	7	42 ± 6	305 ± 31	...	70	...	...	...	
3C 298	-32.2	Q	1.439	1450 ± 70	...		37 ± 12	191 ± 27	238 ± 74	15	1.75	2.25	...	
3C 309.1	-29.5	Q	0.904	3730 ± 190	2350	8	36 ± 133 <sup>a</sup>	114 ± 13	251 ± 84	15	1.40	1.44	0.14	9
3C 318	-25.1	Q	0.752	750	<44.43	3	...	197 ± 64	379 ± 114	6.8	...	...	...	
3C 321	-22.3	NLRG	0.0961	1210 ± 120	30	7	326 ± 6	1006 ± 46	...	482	...	...	...	
3C 325	-24.9	Q	0.860	830 ± 120	2.4	2	27 ± 63 <sup>a</sup>	154 ± 52	35 ± 46 <sup>a</sup>	114	...	...	...	
3C 332	-23.2	Q	0.1515	830 ± 42	...		18 ± 5	52 ± 30	...	224	...	...	...	
3C 334	-28.2	Q	0.555	620	159.5	4	...	75 ± 21	55 ± 24	276	1.59	0.935	...	
3C 368	-26.5	NLRG	1.132	210 ± 30	<0.72	3	39 ± 77 <sup>a</sup>	87 ± 28	79 ± 82 <sup>a</sup>	60	...	...	...	
3C 380	-28.2	Q	0.691	7450 ± 370	7447	8	13 ± 7.5	55 ± 17	78 ± 33	49	1.32	2.48	0.15	10
3C 382	-23.1	Q	0.058	2220 ± 111	188	7	93 ± 23	107 ± 31	...	188	...	...	...	
3C 390.3	-20.8	BLRG	0.056	4450 ± 79	344.37	3	320 ± 7.6	237 ± 6	...	208	...	...	-0.24	9
3C 403	-21.7	NLRG	0.059	2060 ± 100	...		220 ± 30	503 ± 52	...	103	...	...	...	
3C 405	-21.7	NLRG	0.056	371000 ± 18500	314.07	3	834 ± 113	2771 ± 56	430 ± 230	123	0.89	18.5	1.11	11
3C 433	-21.7	NLRG	0.102	3710 ± 190	5	7	193 ± 48	319 ± 93	...	87	...	...	...	
3C 445	-20.6	BLRG	0.056	2030 ± 100	88.52	3	315 ± 47	...	...	730	...	...	1.11	12
3C 459	-23.0	NLRG	0.219	1350 ± 70	1138.26	3	...	962 ± 176	947 ± 351	27	...	...	...	

NOTES.—Col. (3): Emission-line type. NLRG: narrow-line radio galaxy; BLRG: broad-line radio galaxy; WLRG: weak-line radio galaxy; Q: quasar. Col. (5): 5 GHz flux density. Col. (6): Radio core flux at 5 GHz. Col. (7): References for col. (6). Cols. (8), (9), and (10): Flux with uncertainty at 24, 70, and 160  $\mu$ m, respectively. Col. (11): Linear radio size. The references for radio sizes are Akujor & Garrington (1995), Allington-Smith (1984), Gavazzi & Perola (1978), and Nilsson et al. (1993). Col. (12): Spectral index of the hard X-ray emission at 2–10 keV in the rest frame, assuming a power-law SED. Col. (13): Rest-frame 2–10 keV absorption-corrected X-ray flux in the central 2''5 region. Col. (14): Logarithm of the ratio of the intensity of [O III]  $\lambda$ 5007 to H $\beta$ . Col. (15): References for col. (14).

<sup>a</sup> Sources not detected to a 3  $\sigma$  level.

REFERENCES.—(1) Saikia et al. 1987; (2) Fernini et al. 1997; (3) Zirbel & Baum 1995; (4) van Bemmel et al. 1998; (5) 5: Corbin & Boroson 1996; (6) Schmidt 1965; (7) Giovannini et al. 1988; (8) Hough & Readhead 1989; (9) Lawrence et al. 1996; (10) Gelderman & Whittle 1994; (11) Tadhunter et al. 1994; (12) Tadhunter et al. 1993.

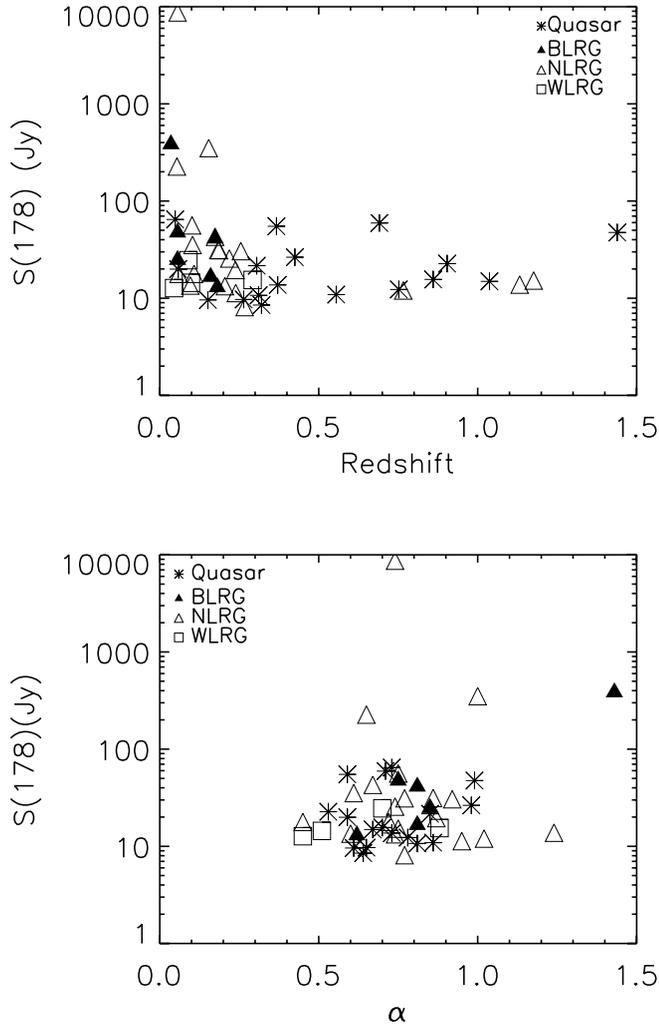


FIG. 1.—Distributions of sources in the plane of the 178 MHz flux vs. redshift (*top*) and 178 MHz flux vs. spectral index  $\alpha$  (*bottom*).

For this study, we divide the sample into two subsamples as described in § 3.1: type I sources including radio quasars and broad-line radio galaxies (BLRGs) and type II sources composed of narrow-line radio galaxies (NLRGs) and weak-line radio galaxies (WLRGs).

To investigate possible selection biases for our sample, in Figure 1 we plot the distribution of all the sources in the plane of 178 MHz flux density versus redshift (*top panel*) and 178 MHz flux density versus spectral index  $\alpha$  (*bottom panel*;  $\alpha$  is defined as  $f_\nu \propto \nu^{-\alpha}$  between 38 and 750 MHz). The top panel indicates for our sample that the 178 MHz flux density spans a range from 6 to  $10^4$  Jy and the redshift a range from 0.03 to 1.4. From this figure, we see that the flux density distributions of type I and II sources are similar. The Kolmogorov-Smirnov (K-S) test indicates a probability of 82% that the two subsamples have the same distributions. However, the sample contains many more high-redshift ( $z > 0.3$ ) type I sources, mainly radio quasars, than high-redshift type II sources. The bottom panel indicates that the spectral indices of the two subsamples are mainly in the range between 0.5 and 1.2. The K-S test gives a probability of 89% that both types have the same distributions of spectral index. On the basis of Figure 1, we find that our sample is not biased in AGN characteristics except that there are relatively more type I sources at high redshift and thus high luminosity.

## 2.2. Infrared Data

Our observations were made with the standard MIPS small field photometry mode. The effective integration time for each source is listed in Table 1. The data were reduced with the MIPS instrument team Data Analysis Tool (DAT) version 2.73 (Gordon et al. 2005).

To obtain the 24  $\mu\text{m}$  fluxes, we performed aperture photometry using the IDL-based image-processing package IDP3 (Schneider & Stobie 2002). We set the radius of the object aperture to 6 pixels ( $15''.0$ ), and we measured the background to be the median flux in a 5 pixel ( $12''.5$ ) wide annulus, at a central radius 11 pixels ( $27''.4$ ) from the centroid of the target. Contamination from other sources within the sky annulus was masked by hand. We multiplied by a factor of 1.146 to correct the measured values for the portion of the point-spread function (PSF) lying outside the source aperture. The pixel-to-pixel fluctuations in the background region were used to calculate the  $1\sigma$  uncertainties. The results are listed in Table 1. Most of the sources are detected at nominally very high signal-to-noise ratios. In addition, there is a calibration uncertainty of up to 10%.

The 70 and 160  $\mu\text{m}$  photometry was reduced in a similar manner. Additional processing steps, such as bad column removal and time filtering, were performed for 70  $\mu\text{m}$  data. The radius of the object aperture at both wavelengths was 3.0 pixels ( $30''$  at 70  $\mu\text{m}$  and  $48''$  at 160  $\mu\text{m}$ ), and the inner and outer radii of the background region were 4 and 8 pixels ( $40''$  and  $80''$  at 70  $\mu\text{m}$ ;  $64''$  and  $128''$  at 160  $\mu\text{m}$ ), respectively. Aperture correction factors of 1.3 and 1.5 were applied to the 70 and 160  $\mu\text{m}$  measurements, respectively. The results of the 70  $\mu\text{m}$  photometry are also listed in Table 1. The five sources detected (in a 3 pixel aperture) at 160  $\mu\text{m}$  are listed in the footnotes to Table 1. There is a calibration uncertainty of up to 20% at both 70 and 160  $\mu\text{m}$ .

To combine the extended sample with the MIPS sample, we need to interpolate the *IRAS* and *ISO* data to calculate the fluxes at the MIPS bands. We use the data points at the two wavelengths closest to the MIPS band for interpolation. Multiple observations at one wavelength are averaged. We assume power-law SEDs to interpolate to the MIPS band and also to propagate the errors. The resulting fluxes are listed in Table 3. Additional errors can arise from the difference between the power law and the real SEDs. By comparing interpolations using a suite of blackbody ( $T \geq 40$  K) and power-law SEDs, we estimate that such errors should be  $<30\%$ .

## 2.3. HST Images

We retrieved archived *HST* data for all sources in our sample, except for 3C 218, which has not been observed. The images were taken with the Wide Field and Planetary Camera 2 (WFPC2), generally with the F555W or F702W filters. The data were processed through the PODPS (Post Observation Data Processing System) pipeline to remove bias and flat-field artifacts (Biretta et al. 1996). Individual exposures in an observation were combined to remove cosmic-ray events. For observations with only one exposure, the cosmic rays were masked by interpolating over them.

## 2.4. Chandra Data

We retrieved data from the *Chandra* archive for 19 sources observed with the Advanced CCD Imaging Spectrometer (ACIS). Data reduction and analysis were performed using CIAO 3.0.2. The level 2 event file was made from the level 1 event file after correction for gain, aspect, and charge transfer inefficiency, and also after PHA randomization and destreaking. We used the light

curve to remove solar flares. Inspection of the images showed that there was severe pileup in the central region of 3C 390.3 where a hole without counts was present. The nuclei of 3C 348 and 3C 173.1 had too few counts for our analysis, and they were dropped from the X-ray sample. For the remaining sources, we extracted the spectra of the nuclear region with an aperture diameter of  $2''.5$  around the peak pixel and then fitted the rest-frame 2–10 keV spectra using an absorbed power law. Finally, we computed the absorption-corrected hard X-ray fluxes, which are listed in column (10) of Table 2 and column (13) of Table 3. The photon spectral indices are listed in column (9) of Table 2 and column (12) of Table 3.

### 3. ANALYSIS

#### 3.1. Division of the Sample into Quasars and Galaxies

We classified the sources as type I (radio quasar or BLRG) or type II (NLRG or WLRG) on a consistent basis. Emission-line types were obtained from the literature. The division between radio quasars and BLRGs was based on absolute  $B$  magnitude. We retrieved the apparent Johnson  $B$  magnitude from NED, originally from Sandage et al. (1965), Smith & Heckman (1989), and de Vaucouleurs et al. (1991). For those sources without available blue magnitudes, we took  $V$  magnitudes from Spinrad et al. (1985) and assumed  $\langle B - V \rangle = 0.3$  mag. The conversion formula from the apparent magnitude to absolute magnitude is

$$M = m - 5 \log D_L + 5 - K(z) - A_m, \quad (1)$$

where  $M$  and  $m$  are absolute magnitude and apparent magnitude, respectively,  $D_L$  is the luminosity distance,  $K(z)$  is the  $K$ -correction at the redshift  $z$ , and  $A_m$  is the Galactic extinction. We compute  $A_m$  using NED. The majority of our sample are in luminous elliptical galaxies; we obtained  $K$ -corrections for such galaxies from Pence (1976). We assumed  $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_M = 0.3$ , and  $\Omega_\Lambda = 0.7$ . The resultant absolute blue magnitudes are listed in column (2) of Tables 2 and 3. Radio quasars have power-law SEDs, typically with a spectral index of 0.5. Therefore, we also calculated the absolute  $B$  magnitude for all sources using the  $K$ -correction based on a power-law SED with a spectral index of 0.5.

We defined as quasars those broad-line sources with an absolute  $B$  magnitude  $< -23$  mag and as BLRGs those with fainter absolute  $B$  magnitudes. Only four sources have ambiguous classifications. 3C 318, 3C 325, 3C 332, and 3C 382 were classified as radio quasars using the  $K$ -correction based on the SED of normal elliptical galaxies, while they were classed as radio galaxies if we assumed that their optical SEDs were power laws. The remaining galaxies without broad lines were classified as NLRGs or WLRGs according to the strength of their emission lines. Column (3) of Tables 2 and 3 lists the results. There are 17 radio quasars, six BLRGs, 20 NLRGs, and four WLRGs. We emphasize that the ambiguous classifications of a few sources do not affect the results of this paper.

#### 3.2. Spectral Energy Distribution

For each source, we used NED to compile the spectral energy distribution (SED) from radio to millimeter, as presented in Figure 2. The radio and millimeter-wave SEDs of these sources are smoothly steepening power laws associated with synchrotron emission. This behavior provides the basis for us to extrapolate to determine the nonthermal contribution to the IR emission. This process requires a synchrotron radiation model and good high-frequency data, since the break frequency of the

synchrotron emission occurs at  $\sim 1$  GHz (Polletta et al. 2000). We used a parabola approximation (Andreani et al. 2002) to fit the synchrotron emission. The spectrum in this model is given by

$$\log F_\nu = C + \frac{1}{2A} (\log \nu - \log \nu_t)^2, \quad (2)$$

where  $C$  is a constant,  $\nu_t$  characterizes the spectral break (i.e., where the nominal optical depth is unity), and  $1/A = 2\alpha_1 - \alpha_2$ , where  $\alpha_1$  and  $\alpha_2$  are the spectral indices above and below the break, respectively. For each source, we adjusted  $C$ ,  $A$ , and  $\nu_t$  to fit all data at wavelengths longer than 1 mm. Figure 2 shows the results; the extrapolation is well constrained, since most sources have high-frequency data and the model can usually fit the data well. The IR emission is generally well above the non-thermal extrapolation. Five sources, 3C 218, 3C 315, 3C 348, 3C 349, and 3C 380, seem to be exceptions: they have IR fluxes below the nonthermal extrapolation at one or more bands. Except for 3C 380, the remaining four sources have no submillimeter observations, and thus their IR emission can be thermal emission by dust if the radio spectrum turns over at very high frequencies. Since their 24–70  $\mu\text{m}$  IR color is redder than the nonthermal continuum, we argue for the thermal nature of the IR emission for these four sources. This hypothesis is confirmed by a mid-IR spectrum of 3C 218 that shows polycyclic aromatic hydrocarbon emission (our unpublished data). The IR flux of 3C 380 is along the nonthermal extrapolation as shown in Figure 2; Bloom et al. (1994) find that the radio spectrum is flat from around 1 cm up to 1100  $\mu\text{m}$ , implying that the non-thermal contribution is significant at infrared wavelengths. The 5 GHz radio emission mainly comes from a region less than  $2''$  across, as shown by comparing  $F_{51}$  and  $F_{5c}$  in Table 3. VLBI observations of the milliarcsecond-scale structure of this compact core reveal a one-sided core jet (Wilkinson et al. 1990; Polatidis & Wilkinson 1998). The total flux of all compact components of the core jet is 2–5 Jy at 5 GHz, contributing 30%–60% of the total flux. This radio core with flat spectrum may make a substantial nonthermal contribution to the infrared emission of 3C 380. Given the ambiguities in the origin of the infrared emission, we do not use this source in the following analysis.

We also evaluated contamination from stellar light in the host galaxy. The stellar light in radio quasars should be negligible. To estimate the stellar contribution from the other host galaxies, we used the spectral template for a normal elliptical galaxy over the spectral range from 1400  $\text{\AA}$  to 2.75  $\mu\text{m}$  (M. Rieke 2004, private communication). The template was shifted by  $(1+z)$  and then normalized at 4405  $\text{\AA}$  to the apparent  $B$  magnitude. The dotted line in Figure 2 shows the stellar emission of the host galaxy; the contribution in the mid-IR (MIR) and FIR wavelength ranges will be negligible.

We conclude that the IR emission of most of our sample of radio-loud galaxies and quasars is mainly thermal IR emission by dust, except for 3C 380.

## 4. DISCUSSION

### 4.1. Energy Source for IR Emission

We use several methods to assess the relative contributions of forming stars and the AGNs in heating the dust in our sample of radio-loud AGNs. We find that star formation provides less than 50% of the IR luminosity in most sources.

#### 4.1.1. Extension of the IR Emission Region

The MIPS 24  $\mu\text{m}$  images do not resolve the sources. The beam diameter of  $\sim 6''$  corresponds to  $\sim 10$  kpc at a redshift of

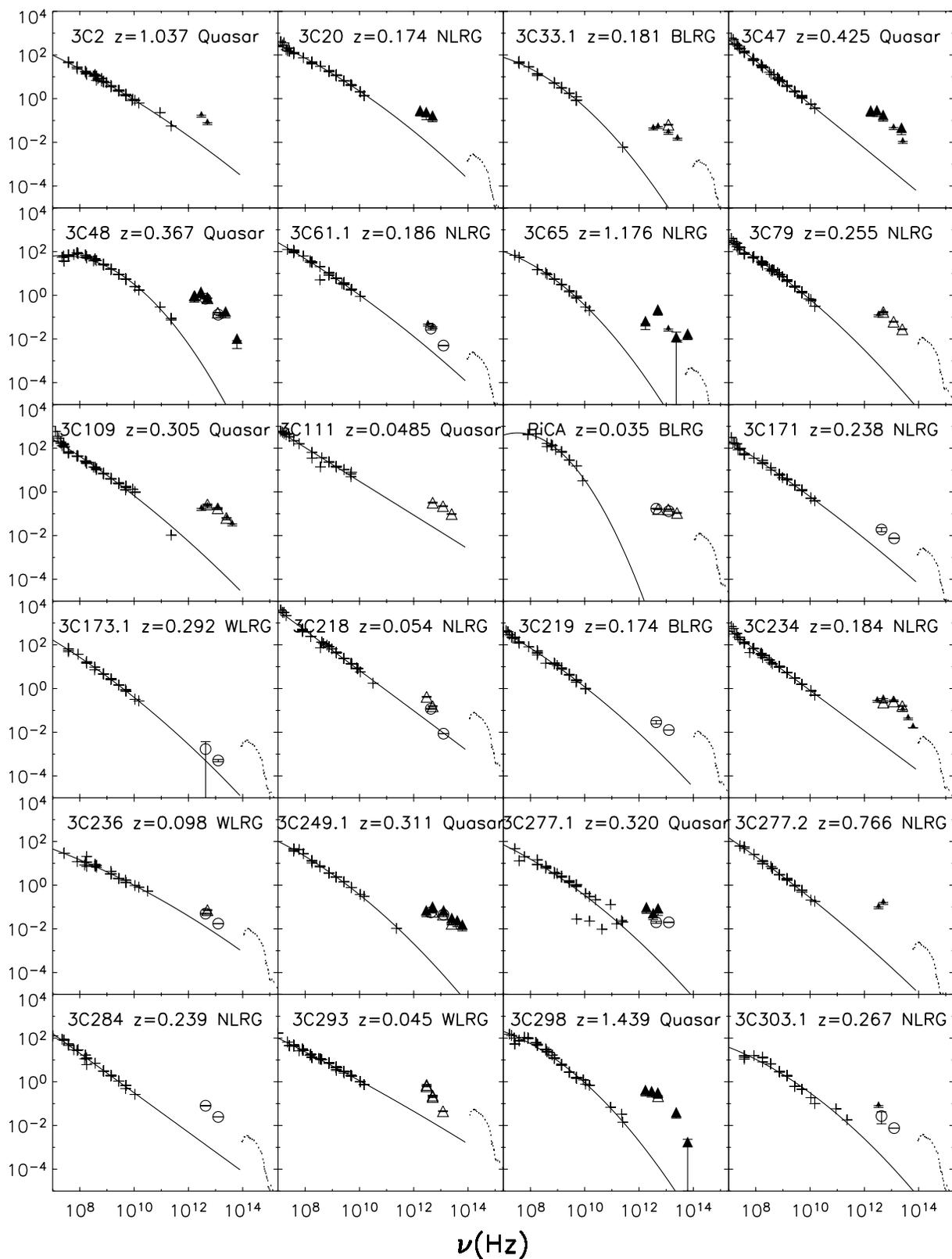


FIG. 2.—SEDs of all sources. The  $1\sigma$  error is used in the plot. The crosses are the radio and millimeter photometry data from NED. The solid line is the parabola model for the synchrotron emission. The open circles, open triangles, and filled triangles denote MIPS, IRAS, and ISO data, respectively. The dotted line for radio galaxies is the template of stellar light for a normal elliptical galaxy, normalized to the apparent  $B$  magnitude. “Quasar,” “BLRG,” “NLRG,” and “WLRG” indicate quasars, broad-line radio galaxies, narrow-line radio galaxies, and weak-line radio galaxies, respectively.

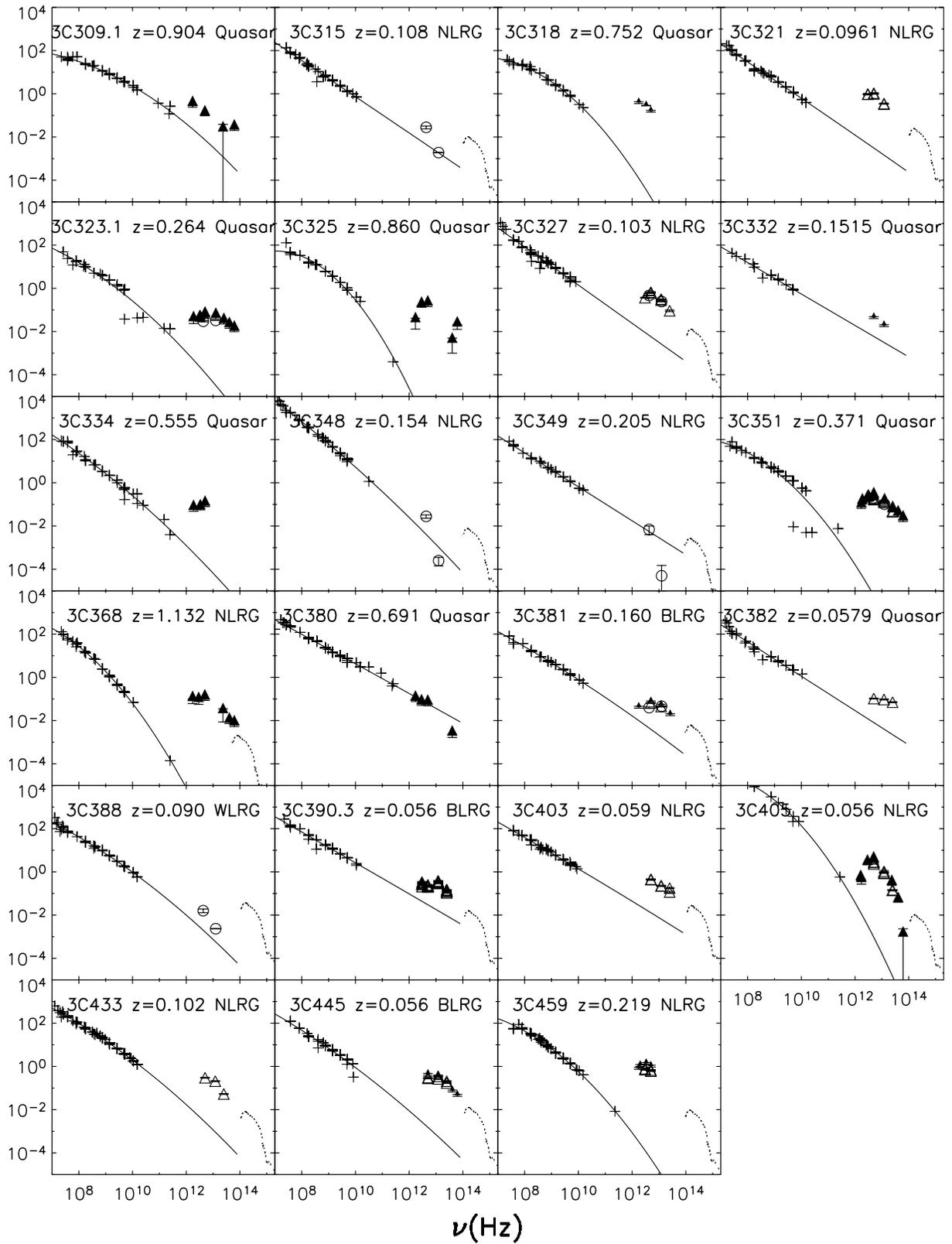


FIG. 2.— *Continued*

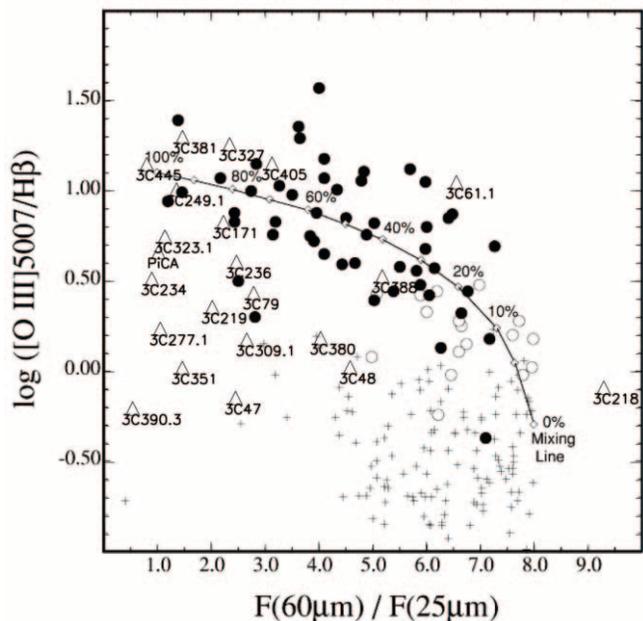


FIG. 3.—IR color vs. emission-line ratio. The solid line is a hypothetical mixing line on which the AGN fraction is labeled. This figure is from Kewley et al. (2001), with our sources added. The open triangles denote our sources. Filled circles, open circles, and plus signs denote AGNs, ambiguous classification, and starbursts, respectively, in Kewley et al. (2001). Note that § 4.2.1 shows that the torus may have significant optical depth at  $24 \mu\text{m}$  and thus the IR color underestimates the fraction of AGN contributions for type II AGNs.

0.1. We convolved the *HST* image with the PSF of MIPS at  $24 \mu\text{m}$  created by STINYTIM and found that the  $24 \mu\text{m}$  image should show some structure for low-redshift ( $z < 0.3$ ) sources if the IR emission is from the entire host galaxy. Thus, the IR emission is constrained to the central region.

#### 4.1.2. Emission-Line Ratio and IR Color

Baldwin et al. (1981), Osterbrock & de Robertis (1985), and Veilleux & Osterbrock (1987) have developed spectral diagnostics to classify emission-line galaxies and determine the dominant energy source, star formation or an active nucleus. They compare two emission-line ratios combining high- and low-excitation lines, such as  $[\text{O III}] \lambda 5007/\text{H}\beta$ ,  $[\text{N II}] \lambda 6583/\text{H}\alpha$ , or  $[\text{S II}] (\lambda 6716 + \lambda 6731)/\text{H}\alpha$ , in a two-dimensional classification diagram.

The dust heated by an AGN is usually warmer than that heated by star formation, and thus the IR color can be used instead of one emission-line ratio for classification diagnostics (Kewley et al. 2001). We use  $[\text{O III}] \lambda 5007/\text{H}\beta$  and IR color to diagnose the dominant source of energy for the IR emission. The data for the ratio  $[\text{O III}] \lambda 5007/\text{H}\beta$  are collected from the literature, and the extinction corrections follow Veilleux & Osterbrock (1987). Our extinction estimates assume an intrinsic  $I(\text{H}\alpha)/I(\text{H}\beta) = 3.1$  (Kewley et al. 2001). For several sources, we use the ratio of equivalent widths of the emission lines because the flux ratio is not available. The extinction corrections are small in virtually all cases. Some sources could not be corrected for extinction because there are no measurements of  $\text{H}\alpha$ . The errors introduced by uncorrected line strengths should be negligible, given the small corrections for the other sources.

Figure 3 shows the distribution of 22 sources in the emission-line ratio versus IR color plot. The IR colors are defined as the ratios of  $60 \mu\text{m}$  flux densities to  $24$  or  $25 \mu\text{m}$  ones. For sources without  $60 \mu\text{m}$  measurements, the flux densities were obtained

by interpolation as in § 2.2. A large  $[\text{O III}] \lambda 5007/\text{H}\beta$  ratio and warm IR color indicate significant AGN activity, i.e., the upper left region of Figure 3. The lower right part of the figure is the locus of star formation. We use the hypothetical mixing line (Kewley et al. 2001) in Figure 3 to estimate the percentage contribution of star formation. Most of our sources lie close to the region delineated by confirmed AGNs (*filled circles*), and for them we conclude that the AGN contributes  $>50\%$  of the total power. However, for a few sources, it appears that the contribution from star formation can be dominant, much higher than the estimation made by IR color alone (Polletta et al. 2000).

In § 4.2.1, we show that the circumnuclear torus may have significant optical depth at  $24 \mu\text{m}$  and so the IR color of type II AGNs may be reddened through obscuration by the torus. Thus, Figure 3 may underestimate the fraction of the AGN contribution for type II AGNs.

#### 4.1.3. Relation of IR Emission to the Central Hard X-Ray Emission

Since the thermal IR emission appears usually to be powered by the nuclear engine, under the unified model we might expect a relation between IR luminosity and nuclear luminosity at other wavelengths. Such a relation might be hidden at wavelengths with strong obscuration by the circumnuclear torus. Hard X-rays are largely immune from such effects. The weakness of the correlation between hard X-ray flux and core radio flux at 5 GHz as shown in Table 4 indicates that the hard X-ray emission for our sources is mainly from the accretion disk and other processes around the central engine, not from the beamed emission. Hard X-rays from the accretion disk are believed to provide a reasonably isotropic estimation of the nuclear luminosity.

Figure 4 compares the rest-frame 2–10 keV absorption and  $K$ -corrected X-ray flux in the central  $2''5$  region and the  $70$  and  $24 \mu\text{m}$   $K$ -corrected flux densities. Because of the inhomogeneity of our sample, we compare  $K$ -corrected flux densities rather than luminosities. The spectral indices of the power laws assumed for the  $K$ -corrections of the X-ray measurements are listed in column (9) of Table 2 and column (12) of Table 3. The  $K$ -corrections for the IR bands were calculated assuming a power-law SED with spectral index of 1. The Kendall  $\tau$  test on these data (see Table 4) yields  $S$  values of 0.05 and 0.09, respectively, at  $24$  and  $70 \mu\text{m}$ , showing only 5% and 9% probabilities, respectively, that the measurements are uncorrelated.

Except for 3C 380, all sources in Figure 4 have negligible nonthermal IR emission. 3C 321 is well above the correlation in Figure 4 and may have significant star formation activity. Additional evidence for active star formation in 3C 321 includes the facts that 3C 321 contains two close nuclei (Roche & Eales 2000) and large amounts of star formation may be triggered by mergers

TABLE 4  
KENDALL  $\tau$  TEST

Relation	$r_{\text{lum}}$	$S_{\text{lum}}$	$r_{\text{flux}}$	$S_{\text{flux}}$
X-ray vs. $70 \mu\text{m}$ .....	...	...	0.32	0.09
X-ray vs. $24 \mu\text{m}$ .....	...	...	0.37	0.05
X-ray vs. radio core .....	...	...	0.30	0.14
IR color vs. $R$ parameter .....	...	...	-0.37	0.04
178 MHz vs. $70 \mu\text{m}$ (all) .....	...	...	0.25	0.02
178 MHz vs. $70 \mu\text{m}$ (quasars) .....	...	...	0.68	0.0002
Radio size vs. $24 \mu\text{m}$ .....	-0.01	0.96	...	...
Radio size vs. $70 \mu\text{m}$ .....	-0.11	0.52	...	...

NOTE.—The  $r$ -value indicates the rank correlation coefficient, and the  $S$  value indicates the two-sided significance of the deviation from zero.

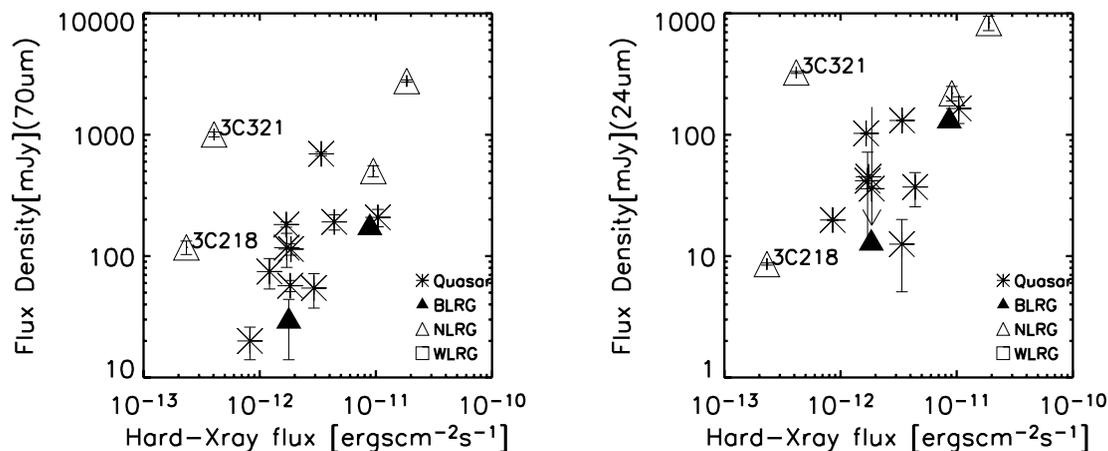


FIG. 4.—Correlation of  $K$ -corrected  $70 \mu\text{m}$  flux density with  $1 \sigma$  error,  $K$ -corrected  $24 \mu\text{m}$  flux density with  $1 \sigma$  error, and central  $K$ -corrected hard X-ray flux corrected for absorption.

(Sanders et al. 1988); and that Tadhunter et al. (1996) find that the AGN fraction can be as low as 26% of the UV continuum by fitting the observed spectra of 3C 321.

The correlation indicates that the thermal IR emission is associated primarily with the nuclear output, not with processes such as star formation that would operate independently of nuclear power. Thus, the IR emission is largely the emission of dust heated by the central engine. Because of the lack of suitable X-ray detections, the radio galaxies are relatively poorly represented in Figure 4, but there is no reason to expect them to behave differently from the other sources.

For the following discussion, we fit the IR/X-ray correlation in luminosity rather than flux density, since converting to this form and fitting the slope reduces the uncertainties due to our rather crude  $K$ -corrections. Excluding 3C 380 and 3C 321, the fits are given by  $\log L_{70} = 1.68 + 0.89 \log L_X$  and  $\log L_{24} = 1.21 + 0.93 \log L_X$ . The dispersion of the relation is given by the relative standard deviation defined by  $\langle [(L_{\text{obs}} - L_{\text{theo}})/L_{\text{theo}}]^2 \rangle^{0.5}$ , where  $L_{\text{obs}}$  is the observed IR luminosity and  $L_{\text{theo}}$  is the theoretical IR luminosity heated by the central black hole, estimated from the fits discussed above. The result is 1.4 and 0.7 for the  $70$  and  $24 \mu\text{m}$  relation, respectively. We can derive a rough upper limit to the contribution of star formation by assuming that all of the scatter arises from this process. The dispersion values imply that the contribution from star formation is smaller than 60% and 40% at  $70$  and  $24 \mu\text{m}$  rest-frame wavelengths, respectively. This result is consistent with the conclusion from our emission-line ratio versus IR color analysis.

#### 4.2. Tests of Unification Models

Since most of the IR emission from these sources seems to be associated with the AGN, we can use the IR data to probe unification models. We describe two types of test: (1) to see whether the distribution of physical parameters is consistent with an obscuring circumnuclear torus and beamed emission by a jet, observed over a range of viewing angles; and (2) to check whether the relations between selected physical parameters are the same for the radio quasars and galaxies.

##### 4.2.1. IR Color versus $R$ Parameter

Because of beaming, the emission of the radio core should be orientation dependent. Thus, the radio compactness, the  $R$  parameter, can be used to indicate the viewing angle with respect to the orientation of the radio jet (Orr & Browne 1982). Here we define  $R = F_{5c}/F_{5t}$ , where  $F_{5c}$  and  $F_{5t}$  are the core and total

radio fluxes at 5 GHz, respectively.  $R = 1$  corresponds to the direction along the radio jet, and the smaller  $R$ , the larger the viewing angle (we assume that the torus is perpendicular to the jet, so  $R$  is taken as an indication of the viewing angle relative to the torus, as well as the jet). We obtained from NED the total 5 GHz radio emission listed in column (5) of Tables 2 and 3, and from the literature the radio core emission listed in column (6) of Tables 2 and 3. We plot the IR color defined by  $F_{70}/F_{24}$  as a function of the  $R$  parameter in Figure 5. In this figure, we do not include sources with upper limits to their IR fluxes, nor the sources with possibly significant nonthermal components or large star formation contributions ( $\sim 80\%$  in Fig. 3).

We find a trend that redder IR color corresponds to a smaller  $R$  parameter and different emission-line types fall in different regions in the plot, qualitatively consistent with the prediction

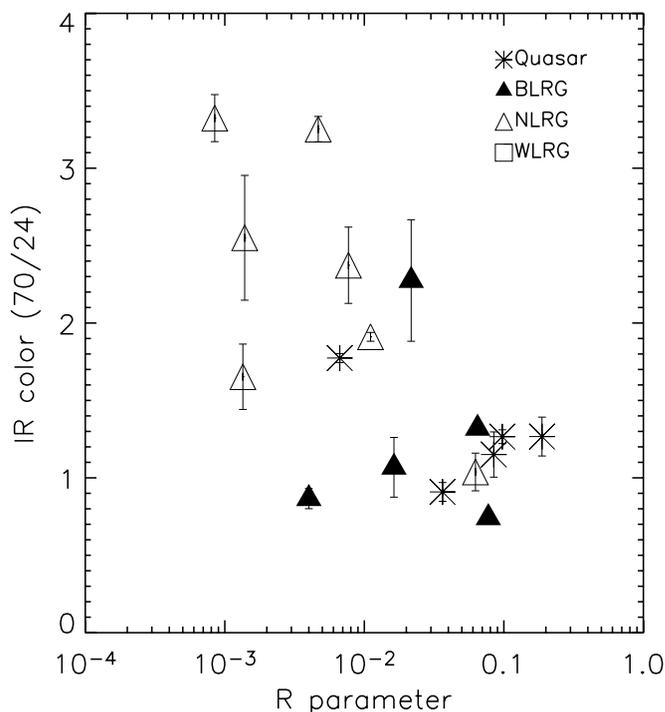


FIG. 5.—Correlation between IR color with  $1 \sigma$  error and  $R$  parameter. The IR color is defined as the ratio of  $70 \mu\text{m}$  flux to  $24 \mu\text{m}$  flux. The  $R$  parameter is defined as the ratio of the core radio flux to the total radio flux at 5 GHz. The solid line shows the least-squares fit.

of the unification model. The overlapping between different emission-line types of source in the plot is possibly because the  $R$  parameter depends on other characteristics besides the viewing angle (Orr & Browne 1982), such as the core Lorentz factor, and because intrinsic dispersion in the radio core and lobe emission causes dispersion in the  $R$  parameter (Lonsdale & Barthel 1987). The least-squares fit to the relation in Figure 5 is given by  $F_{70}/F_{24} = 0.35 - 0.74 \log R$ . The corresponding Kendall  $\tau$  test result given in Table 4 indicates a 96% probability of a significant correlation. The observed range of IR color of a factor of  $\sim 2.5$  indicates that optical depth effects are still significant at  $24 \mu\text{m}$  in the typical torus in an FR II radio galaxy. In contrast, Heckman et al. (1994) compared  $60 \mu\text{m}$  fluxes between narrow-line AGNs and broad-line AGNs and found that they were almost the same, suggesting that the torus is optically thin at  $60 \mu\text{m}$ .

For 3C 405, with the smallest  $R$  parameter in our sample, the absorbed power-law fit to the hard X-ray spectrum shows that the hydrogen column density is  $N_{\text{H1}} = 10^{23} \text{ cm}^{-2}$ . Using  $A_V = 0.62 \times 10^{-21} N_{\text{H1}}$  (Savage & Mathis 1979), where  $A_V$  is the visual extinction, we have  $A_V = 62$ . Taking  $A_V/A_{70} = 364$ ,  $A_{70} = 0.17$ , indicating that the extinction is small at  $70 \mu\text{m}$  even when we view the AGN through the torus, in agreement with our conclusion from the color behavior.

However, the extinctions at  $24$  and  $70 \mu\text{m}$  should not be very different;  $A_{24}/A_{70}$  is expected to be around 7. Therefore, to explain the systematic change in optical depth between these two wavelengths may require a specific type of torus model. We hypothesize that there is a temperature gradient along the radial direction of the torus; the inner part of the toroidal disk is closer to the central heating source and hence is hotter than the outer region. To maintain a gradient may require the outer parts of the disk to be heated by energy reradiated from the inner parts, the disk to be warped or flared, or for it to have a porous (or cloudy) structure. Such a temperature gradient may explain the non-single-blackbody IR SED of the AGN as shown in Figure 2. As a result, the  $24 \mu\text{m}$  flux is predominantly emitted by the dust in the inner torus, while  $70 \mu\text{m}$  emission is mainly from the outer region. If the density of the toroidal disk drops with distance from the central region, then the optical depth to the  $24 \mu\text{m}$  emission from the inner region could be large while it is still small to a significant portion of the  $70 \mu\text{m}$  emission from the outer region.

As can be seen in the diagnostic diagram in Figure 3, the reddening due to an edge-on accretion torus could drive a pure AGN spectrum toward the star-forming region. These results indicate that the FIR color is not a completely reliable indicator of star formation activity; an AGN with a large torus inclination angle can also have a red FIR color. Two-dimensional diagrams, such as IR color versus emission-line ratio, may be useful to indicate the level of star formation activity, although they are still not infallible.

Recently, Whysong & Antonucci (2004) argued that the lack of  $12 \mu\text{m}$  emission from some FR I AGNs indicates that they lack a torus. However, if the torus has significant optical depth at  $24 \mu\text{m}$ , the  $12 \mu\text{m}$  emission will be strongly suppressed and thus cannot be used to estimate the intrinsic torus emission.

#### 4.2.2. An Indication of the Torus Opening Angle

We return to Figure 4 to compare the IR and X-ray emission for quasars and radio galaxies. Although the data points in Figure 4 are mainly for radio quasars, the various kinds of radio galaxy follow the relation well. Since the IR emission is the reprocessing of the emission from the accretion disk, especially

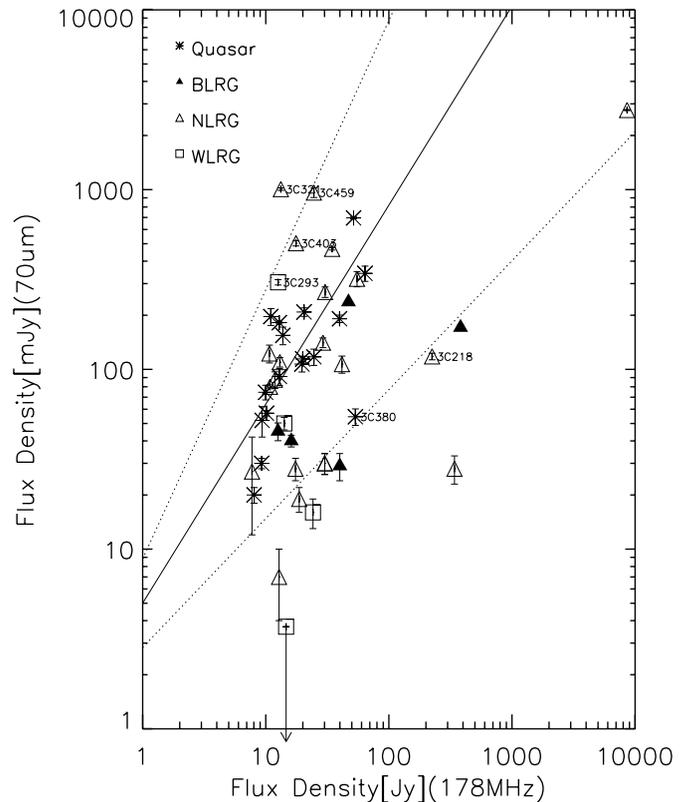


FIG. 6.—Relation of the  $K$ -corrected  $70 \mu\text{m}$  emission with  $1 \sigma$  error and  $K$ -corrected radio emission at  $178 \text{ MHz}$ . The solid line is the least-squares fit to the radio quasars, excluding 3C 380 with substantial contribution by nonthermal core output (see § 3.2), unlike those of the other quasars. The two dashed lines are the  $3 \sigma$  scatter of the relation indicated by the solid line.

optical and UV photons, the IR emission is determined under the unified model by the central intrinsic emission and the torus structure. The torus structure must be very complicated. However, for simplicity, we assume that it is described only by the opening angle and that the light blocked by the torus is reprocessed completely to IR emission; otherwise, it can escape completely. Moreover, we assume that the emission of the torus is isotropic at  $70 \mu\text{m}$  (we also show the behavior at  $24 \mu\text{m}$  for comparison). If the torus opening angle is constant, then the IR emission should be proportional to the X-ray emission. The least-squares fit indicates that the slope is 0.89 and 0.94 for  $70$  and  $24 \mu\text{m}$ , respectively. Neither value is significantly different from unity. Based on the above simple model, such a slope suggests that the torus opening angle does not change with the activity level of the central engine. The radio power of our sources is greater than  $10^{26.5} \text{ W Hz}^{-1}$  at  $178 \text{ MHz}$ , so this result is consistent with the invariance of the opening angle based on the quasar fraction (Willott et al. 2000). The result also indicates that most radio galaxies and radio quasars possess a torus with similar structure, supporting the unification model.

#### 4.2.3. The Relation of IR Emission and 178 MHz Radio Emission

The  $70 \mu\text{m}$  emission and  $178 \text{ MHz}$  radio emission should also both be isotropic, so we can use them to probe unification models for different types of radio source. The relation of the  $K$ -corrected  $70 \mu\text{m}$  flux density to the  $K$ -corrected  $178 \text{ MHz}$  flux density is shown in Figure 6. For the radio, we base  $K$ -corrections on a power-law SED with spectral index of 0.8, while we used a spectral index of 1 at  $70 \mu\text{m}$ . The relation between  $24 \mu\text{m}$  and  $178 \text{ MHz}$  emission is not shown because of

the many upper limits to the  $24\ \mu\text{m}$  flux. Because the 178 MHz flux density is a defining parameter for the sample, Figure 6 includes all the radio galaxy members (in comparison, for example, with Fig. 4, which includes only a fraction). The figure shows that the distributions of radio quasars and radio galaxies are different. Radio quasars except for 3C 380 are constrained in a tight correlation with an  $S$  value of  $3 \times 10^{-3}$  by the Kendall  $\tau$  test. The solid line is the least-squares fit to the radio quasars excluding 3C 380 (see § 3.2); the dashed lines are the  $3\ \sigma$  bounds to the relation indicated by the solid line.

Again, 3C 321 is above the  $3\ \sigma$  bounds. Its behavior may be due to powerful star formation activity triggered by a merger (see § 4.1.3). Three additional galaxies close to the  $3\ \sigma$  high limit (3C 293, 3C 403, and 3C 459) may also have excess IR emission powered by star formation. Nearly one-third of the radio galaxies are below the region between the two dashed lines. Except for 3C 405, Pic A, 3C 218, and 3C 348, the FIR underluminous sources do not show larger radio fluxes compared with radio quasars, so we cannot attribute the behavior in Figure 6 to selection bias. Since these galaxies are underluminous at  $70\ \mu\text{m}$ , we cannot account for their behavior by an additional FIR source such as star formation. We conclude that the simple unification model works less well for the galaxies in the sample than for the quasars; it appears to predict the properties of some galaxies but not others.

We have examined the FIR underluminous galaxies individually to see whether we can understand why they depart from the simple unification model prediction. We looked for explanations in terms of their having a weaker nuclear engine, since the FIR emission is a good indicator of the nuclear accretion power, or of their having higher radio emission because of a special environment where radio emission is easily generated (Barthel & Arnaud 1996; Haas et al. 2004).

**3C 388.**—Based on the relation of the optical core luminosity and radio core emission, Chiaberge et al. (2000) argue that 3C 388 has a FR I nucleus, i.e., weaker than for classic FR II galaxies.

**3C 348.**—The radio morphology of 3C 348 is like neither FR I nor FR II. It is better classified as an intermediate-type radio source. Thus, we may speculate that 3C 348 has a relatively weaker nucleus with respect to normal FR II galaxies.

We have not found a good explanation for the behavior of the remaining galaxies. Their environments are not different from the normal FIR luminous sources. Barthel & Arnaud (1996) find that sources in X-ray clusters show higher radio-to-infrared ratios than noncluster galaxies. This may be due to the upper limit measurements of IR fluxes by *IRAS*; for example, 3C 61.1 and 3C 315 are now detected by MIPS, and their ratios can reach 2.9 and 2.75, respectively, and therefore only one source in the sample of cluster galaxies shows a significantly higher ratio than for field galaxies. No direct evidence indicates that the remaining FIR underluminous sources have weaker nuclei. It may be necessary to modify the simple unification model to explain them. For example, there may be a large range of optical depths at  $70\ \mu\text{m}$ ; the weakly emitting galaxies could then be significantly obscured.

#### 4.3. Compact Steep-Spectrum Sources

Compact steep-spectrum (CSS) and gigahertz-peaked spectrum (GPS) radio sources have similar radio outputs to other radio sources but are substantially more compact, 1–20 kpc. As discussed by O’Dea (1998), IR observations can distinguish a number of hypotheses regarding these objects, most notably whether they are *frustrated* large-scale sources due to a

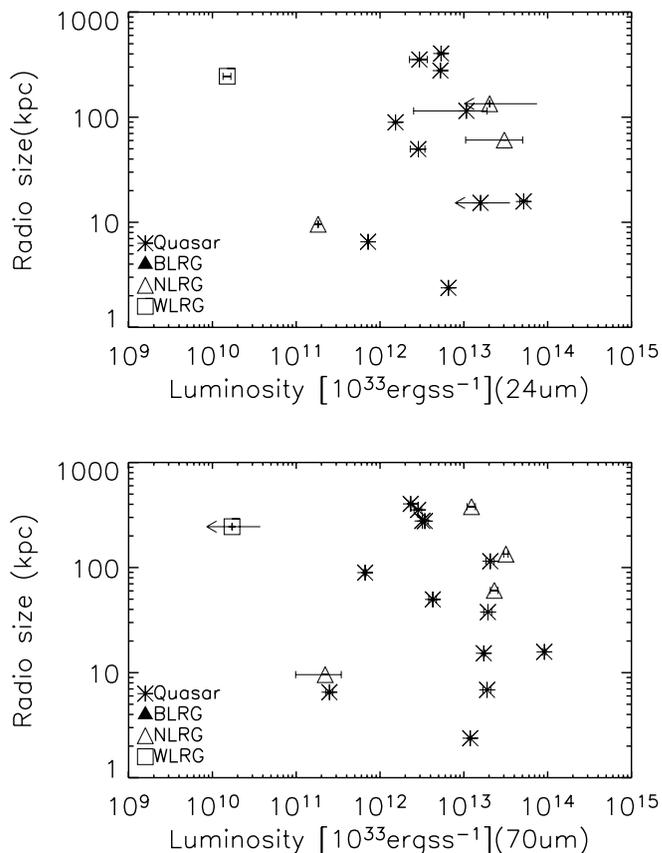


FIG. 7.—Plot of linear radio size vs.  $K$ -corrected FIR luminosity with  $1\ \sigma$  error.

dense interstellar medium that absorbs the energy of the radio-emitting jets. This absorbed energy would be expected to emerge in the FIR. A number of searches have failed to find any effect of the type predicted by the frustrated source model (Heckman et al. 1994; Fanti et al. 2000). Because the FIR detection limits available to these studies were generally inadequate for the measurement of single galaxies, they co-added signals from many galaxies to achieve an average emission level. The levels from the CSS/GPS and control samples are similar, although the significance level of the comparisons is only modest. The comparisons are also subject to uncertainty due to the necessity of stacking detections for higher statistical significance: a few extreme sources can dominate the results. Another probe of these sources is to determine the absorption and hence the density of the surrounding interstellar medium. Pihlström et al. (2003) report  $\text{H I}$  observations that show an increase in ISM density with decreasing radio size. This behavior is qualitatively consistent with the frustrated source model, but Pihlström et al. (2003) show that the ISM density is probably inadequate to confine the jets, unless the  $\text{H}_2/\text{H I}$  ratio is much higher than normal. Fanti et al. (2000) give additional arguments against the frustrated source model. Our data permit another test of the frustrated source model, based on IR data with enough sensitivity to detect individual galaxies.

We identify six CSS sources whose radio sizes are smaller than 20 kpc in our sample. The comparison sample consists of large-scale sources in the redshift range of the CSS sample, from 0.27 to 1.4. Figure 7 plots the linear radio size and IR luminosity. The radio size ranges from 2 to 400 kpc, and IR luminosity is from  $10^{10}$  to  $10^{14} L_{\odot}$ . No correlation is indicated. We conclude that the CSS sources do not show significantly different FIR output from the large-scale radio sources, consistent

with the results of *IRAS* (Heckman et al. 1994) and *ISO* (Fanti et al. 2000). Hes et al. (1995) find that CSS sources are IR-brighter. Their result may be caused by the selection bias that CSS sources in their sample are at high redshift and thus high luminosity. In addition, the lack of an additional IR luminosity component argues against the proposal that these galaxies might be sites of strong star formation induced by the interaction between a jet and ambient matter (Baker et al. 2002).

## 5. CONCLUSIONS

In this paper, we present MIPS observations of steep-spectrum radio quasars and FR II radio galaxies and combine them with the sample detected by *IRAS* and *ISO*. We discuss the nature of the IR emission in this combined sample and its implications for the unification model. The main results are as follows:

1. The IR emission of most sources is thermal. The thermal IR emission of most sources is dominated by dust heated by the AGN.
2. The simple unification model predicts the properties of the radio quasars and some radio galaxies well. However, the prop-

erties of some FIR underluminous galaxies may be inconsistent with a pure unification model in which there are no orientation-independent intrinsic differences among these sources.

3. The behavior of the 70  $\mu\text{m}$ /24  $\mu\text{m}$  color with radio compactness is consistent with the suggestion that a torus that has significant optical depth at 24  $\mu\text{m}$  surrounds the nuclei of the FR II radio galaxies.

4. The CSS sources do not show additional IR emission, arguing against the proposals that these sources reside in extremely dense regions or that they are associated with strong star-forming activity.

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## REFERENCES

- Akujor, C. E., & Garrington, S. T. 1995, *A&AS*, 112, 235  
 Akujor, C. E., Spencer, R. E., Zhang, F. J., Davis, R. J., Browne, I. W. A., & Fanti, C. 1991, *MNRAS*, 250, 215  
 Allington-Smith, J. R. 1984, *MNRAS*, 210, 611  
 Andreani, P., Fosbury, R. A. E., van Bemmel, I., & Freudling, W. 2002, *A&A*, 381, 389  
 Baker, J. C., Hunstead, R. W., Athreya, R. M., Barthel, P. D., de Silva, E., Lehnert, M. D., & Saunders, R. D. E. 2002, *ApJ*, 568, 592  
 Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, *PASP*, 93, 5  
 Barthel, P. D. 1989, *ApJ*, 336, 606  
 Barthel, P. D., & Arnaud, K. A. 1996, *MNRAS*, 283, L45  
 Biretta, J. A., et al. 1996, *Wide Field and Planetary Camera 2 Instrument Handbook*, ed. J. A. Biretta (Baltimore: STScI)  
 Bloom, S. D., Marscher, A. P., Gear, W. K., Teräsanta, H., Valtaoja, E., Aller, H. D., & Aller, M. F. 1994, *AJ*, 108, 398  
 Boroson, T. A., & Oke, J. B. 1984, *ApJ*, 281, 535  
 Chiaberge, M., Capetti, A., & Celotti, A. 2000, *A&A*, 355, 873  
 Corbin, M. R., & Boroson, T. A. 1996, *ApJS*, 107, 69  
 de Grijp, M. H. K., Keel, W. C., Miley, G. K., Goudfrootij, P., & Lub, J. 1992, *A&AS*, 96, 389  
 de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Jr., Buta, R. J., Paturel, G., & Fouque, P. 1991, *S&T*, 82, 621  
 Fanaroff, B. L., & Riley, J. M. 1974, *MNRAS*, 167, 31P  
 Fanti, C., et al. 2000, *A&A*, 358, 499  
 Fernini, I., Burns, J. O., & Perley, R. A. 1997, *AJ*, 114, 2292  
 Gavazzi, G., & Perola, G. C. 1978, *A&A*, 66, 407  
 Gelderman, R., & Whittle, M. 1994, *ApJS*, 91, 491  
 Giovannini, G., Feretti, L., Gregorini, L., & Parma, P. 1988, *A&A*, 199, 73  
 Golombek, D., Miley, G. K., & Neugebauer, G. 1988, *AJ*, 95, 26  
 Gordon, K. D., et al. 2005, *PASP*, 117, 503  
 Granato, G. L., & Danese, L. 1994, *MNRAS*, 268, 235  
 Grandi, S. A., & Osterbrock, D. E. 1978, *ApJ*, 220, 783  
 Haas, M., Chini, R., Meisenheimer, K., Stickel, M., Lemke, D., Klaas, U., & Kreysa, E. 1998, *ApJ*, 503, L109  
 Haas, M., et al. 2004, *A&A*, 424, 531  
 Heckman, T. M., O'Dea, C. P., Baum, S. A., & Laurikainen, E. 1994, *ApJ*, 428, 65  
 Hes, R., Barthel, P. D., & Hoekstra, H. 1995, *A&A*, 303, 8  
 Hough, D. H., & Readhead, A. C. S. 1989, *AJ*, 98, 1208  
 Kellermann, K. I., Sramek, R., Schmidt, M., Shaffer, D. B., & Green, R. 1989, *AJ*, 98, 1195  
 Kewley, L. J., Heisler, C. A., Dopita, M. A., & Lumsden, S. 2001, *ApJS*, 132, 37  
 Lawrence, C. R., Zucker, J. R., Readhead, A. C. S., Unwin, S. C., Pearson, T. J., & Xu, W. 1996, *ApJS*, 107, 541  
 Lonsdale, C. J., & Barthel, P. D. 1987, *AJ*, 94, 1487  
 Nenkova, M., Ivezić, Z., & Elitzur, M. 2002, *ApJ*, 570, L9  
 Neugebauer, G., Miley, G. K., Soifer, B. T., & Clegg, P. E. 1986, *ApJ*, 308, 815  
 Nilsson, K., Valtonen, M. J., Kotilainen, J., & Jaakkola, T. 1993, *ApJ*, 413, 453  
 O'Dea, C. P. 1998, *PASP*, 110, 493  
 Orr, M. J. L., & Browne, I. W. A. 1982, *MNRAS*, 200, 1067  
 Osterbrock, D. E., & de Robertis, M. M. 1985, *PASP*, 97, 1129  
 Pence, W. 1976, *ApJ*, 203, 39  
 Pier, A. P., & Krolik, J. H. 1993, *ApJ*, 418, 673  
 Pihlström, Y. M., Conway, J. E., & Vermeulen, R. C. 2003, *A&A*, 404, 871  
 Polatidis, A. G., & Wilkinson, P. N. 1998, *MNRAS*, 294, 327  
 Polletta, M., Courvoisier, T. J. L., Hooper, E. J., & Wilkes, B. J. 2000, *A&A*, 362, 75  
 Rieke, G. H., et al. 2004, *ApJS*, 154, 25  
 Roche, N., & Eales, S. A. 2000, *MNRAS*, 317, 120  
 Rowan-Robinson, M. 2000, *MNRAS*, 316, 885  
 Saikia, D. J., Salter, C. J., & Muxlow, T. W. B. 1987, *MNRAS*, 224, 911  
 Sandage, A., Véron, P., & Wyndham, J. D. 1965, *ApJ*, 142, 1307  
 Sanders, D. B., Soifer, B. T., Elias, J. H., Madore, B. F., Matthews, K., Neugebauer, G., & Scoville, N. Z. 1988, *ApJ*, 325, 74  
 Savage, B. D., & Mathis, J. S. 1979, *ARA&A*, 17, 73  
 Schmidt, M. 1965, *ApJ*, 141, 1  
 Schneider, G., & Stobie, E. 2002, in *ASP Conf. Ser. 281, Astronomical Data Analysis Software and Systems XI*, ed. D. A. Bohlender, D. Durand, & T. H. Handley (San Francisco: ASP), 382  
 Siebenmorgen, R., Freudling, W., Krügel, E., & Haas, M. 2004, *A&A*, 421, 129  
 Simpson, C., Ward, M., Clements, D. L., & Rawlings, S. 1996, *MNRAS*, 281, 509  
 Smith, E. P., & Heckman, T. M. 1989, *ApJS*, 69, 365  
 Solórzano-Iñarrea, C., & Tadhunter, C. N. 2003, *MNRAS*, 340, 705  
 Spinrad, H., Marr, J., Aguilar, L., & Djorgovski, S. 1985, *PASP*, 97, 932  
 Tadhunter, C. N., Dickson, R. C., & Shaw, M. A. 1996, *MNRAS*, 281, 591  
 Tadhunter, C. N., Metz, S., & Robinson, A. 1994, *MNRAS*, 268, 989  
 Tadhunter, C. N., Morganti, R., di Serego-Alighieri, S., Fosbury, R. A. E., & Danziger, I. J. 1993, *MNRAS*, 263, 999  
 Urry, C. M., & Padovani, P. 1995, *PASP*, 107, 803  
 van Bemmel, I., & Barthel, P. 2001, *A&A*, 379, L21  
 van Bemmel, I., & Dullemond, C. P. 2003, *A&A*, 404, 1  
 van Bemmel, I. M., Barthel, P. D., & Yun, M. S. 1998, *A&A*, 334, 799  
 Veilleux, S., & Osterbrock, D. E. 1987, *ApJS*, 63, 295  
 Whyson, D., & Antonucci, R. 2004, *ApJ*, 602, 116  
 Wilkinson, P. N., Tzioumis, A. K., Akujor, C. E., Benson, J. M., Walker, R. C., & Simon, R. S. 1990, in *Parsec-Scale Radio Jets*, ed. J. A. Zensus & T. J. Pearson (Cambridge: Cambridge Univ. Press), 152  
 Willott, C. J., Rawlings, S., Blundell, K. M., & Lacy, M. 2000, *MNRAS*, 316, 449  
 Zirbel, E. L., & Baum, S. A. 1995, *ApJ*, 448, 521